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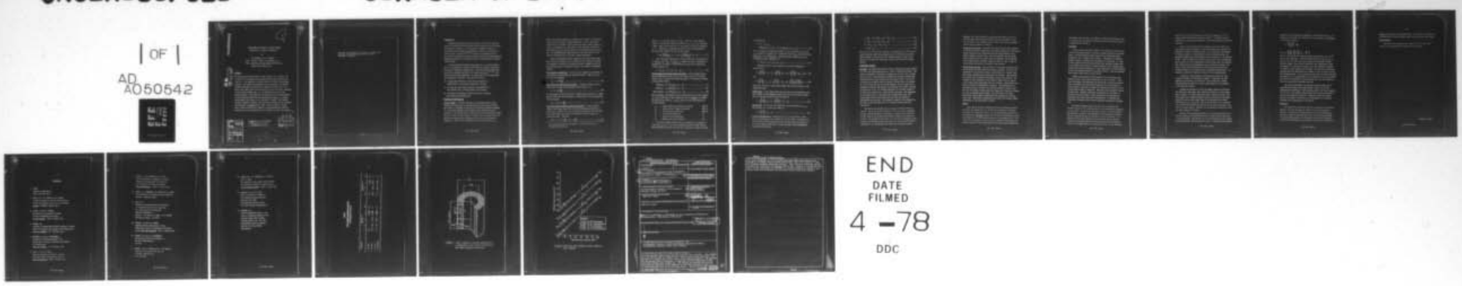

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DEVELOPMENT AND EVALUATION OF HEAT TRANSFER EQUATIONS FOR A MODEL OF CLOTHED MAN

by

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ABSTRACT

Two equations have been derived for heat transfer from a cylinder. The cylinder had a wet surface and was wrapped with a layer having uniform properties. One equation is a special case of the other, a more general equation. The equation for the special case is equivalent to equations currently being used to describe heat transfer from clothed men. The special case implies that current equations are valid when sweat evaporates at the body skin surface only, i.e. no evaporation may occur at the clothing surface. Both (forms of the) equations gave good representation of the steady state data which were obtained from studies on a clothed, heated manikin with either a wet or dry skin ($r > 0.99$). The clothing resembled industrial clothing. Skin (and hence clothing) wetness increased the conductance of sensible heat by 32%. Failure to account for this effect caused insensible heat transfer to be underestimated by 13% and a systematic error was introduced into the prediction of total heat transfer.

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The views of the author do not purport to reflect the positions of the Department of the Army or the Department of Defense.

INTRODUCTION

Equations which describe the heat transfer from clothed humans are required in analytical models of man's thermal response to work in varying environmental conditions. It is becoming increasingly accepted that workers must be protected from the dangers of working in environments of extreme stress. Recent work[10, 11] on nude men has demonstrated that heat transfer equations can be used to develop rational, and physiologically meaningful procedures for protecting workers from the dangers of excessive thermal stress.

The process of heat transfer from clothed men is extremely complex and it is not possible to develop the relevant heat transfer equations on the basis of theoretical arguments only. Idealized models therefore have been used to establish the form of the required equations[6, 7, 15]: the present work was aimed, generally, at contributing to, and increasing the understanding of such models. The specific aims were:

a) to apply basic theories of heat and mass transfer to a simple model of a man wearing conventional clothing.

b) to relate the heat transfer equations to measurements of heat transfer from a clothed, heated, copper manikin.

c) to evaluate the equations currently being used to describe heat transfer from clothed men.

THEORETICAL CONSIDERATIONS

Idealized Model: In recent theoretical and experimental work on heat transfer from nude humans it has been shown that heat transfer from the body surface is analogous to that which occurs from an equivalent cylinder[12]. The present analysis of heat transfer from clothed man is based, similarly, on the consideration of heat transfer from an equivalent cylinder. However, in this case the cylinder is wrapped with a homogeneous layer (of idealized clothing) having uniform heat transfer and vapour diffusive properties, k ($W/m^2\ ^oC$) and h ($kg/m^2\ kPa$) respectively, (See Fig. 1).

Assume the interface between the cylinder and the layer to be fully wet[+] (with water) and to have a uniform temperature, t_s (°C). The vapour pressure at the interface is then the saturated water vapour pressure, p_s (kPa), at temperature t_s. The diameter of the equivalent cylinder is represented by D_{eq} (m) and the diameter of the cylinder plus layer by D_o (m). The temperature and vapour pressure at the outer surface of the layer are represented by t_o (°C) and p_o (kPa) respectively.

Within the homogeneous layer, assume that all heat transfer takes place either by conduction, or by a process of mass diffusion involving the evaporation of water at the cylinder surface. Assumed also that no heat transfer occurs in the axial direction; end effects are therefore ignored.

Heat Transfer by Conduction: The rate of heat transfer by conduction, at a cylindrical surface having unit length and radius r (See Fig. 1) is given by the expression

$$J_k = - k\, 2\pi r \frac{dt}{dr} \quad \text{.......} \quad (1)$$

Heat Transfer by Diffusive Mass Transfer: A similar expression can be written for the rate of mass transfer at this surface, i.e.

$$\dot{m} = - h\, 2\pi r \frac{dp}{dr} \quad \text{.......} \quad (2)$$

If each kilogram of water vapour has a thermal energy content of λ' (J/kg) then the above rate of mass transfer is responsible for the following rate of heat transfer.

$$J_e = - 2\pi h\, \lambda'\, r \frac{dp}{dr} \quad \text{.......} \quad (3)$$

Total Heat Transfer Through a Single Layer System: If heat is being supplied from within the cylinder to the cylinder/layer interface at a steady rate, J (W/m²), then, in a condition of equilibrium the same total heat transfer must occur across all cylindrical surfaces within the homogeneous layer. Therefore,

$$\pi D_o\, J = - 2\pi\, k\, r \frac{dt}{dr} - 2\pi\, h\, \lambda\, r \frac{dp}{dr} \quad \text{.......} \quad (4)$$

+ The more general case of a partially wet interface will not be considered in this paper.

Where $\lambda = \lambda'$ - the heat content, per kg, of the water on the cylinder surface. Provided the temperature difference $(t_s - t_o)$ is not too large, λ may be taken as the latent heat of vaporization of water at temperature t_s [14]. Integration of equation 4 yields the following expression for the total heat transfer from the cylinder surface.

$$J = \frac{2\,k}{D_o \ln (D_o/D_{eq})}\,(t_s - t_o) + \frac{2\,h\,\lambda}{D_o \ln (D_o/D_{eq})}\,(p_s - p_o) \;\ldots\ldots\ldots \quad (5)$$

For a particular combination of cylinder and layer, the terms $2\,k/D_o \ln (D_o/D_{eq})$ and $2\,h/D_o \ln (D_o/D_{eq})$ are constant and may be considered as properties of the system. Representing them by K_a and H_a respectively reduces equation 5 to

$$J = K_a\,(t_s - t_o) + H_a\,\lambda\,(p_s - p_o) \;\ldots\ldots\ldots \quad (6)$$

<u>Heat Exchange with the Surrounding Environment</u>: Heat exchange between a smooth cylinderical surface, such as the external surface of the layer shown in Fig. 1, and the surrounding environment is described by the three equations which follow:

$$\text{Radiation:}\quad J_r = (D_o/D_{eq})\,h_r\,(t_o - t_r) \;\ldots\ldots\ldots \quad (7)$$

$$\text{Convection:}\quad J_c = (D_o/D_{eq})\,h_c\,(t_o - t_a) \;\ldots\ldots\ldots \quad (8)$$

$$\text{Mass Transfer:}\quad J_m = (D_o/D_{eq})\,h_m\,\lambda\,(p_o - p_a) \;\ldots\ldots\ldots \quad (9)$$

The ratio D_o/D_{eq} is included in order to express the rates of heat transfer J_r, J_c and J_m as rates of heat transfer per unit of <u>cylinder</u> area (W/m²). It should be noted that h_r, h_c and h_m refer to a unit area measured at the layer surface.

h_r	=	linear radiant heat transfer coefficient	W/m² °C
h_c	=	convective heat transfer coefficient	W/m² °C
h_m	=	vapour transfer coefficient	kg/m kPa
t_r	=	mean radiant temperature	°C
t_a	=	ambient dry-bulb temperature	°C
p_a	=	ambient water vapour pressure	kPa

To simplify further analysis, the environments will be confined to those where $t_r \equiv t_a$ [5]. The net heat exchange between the layer surface and environment is then given by the sum of equations 7, 8 and 9, as shown

in equation 10.

$$J = J_r + J_c + J_m$$

$$= (D_o/D_{eq})(h_r + h_c)(t_o - t_a) + (D_o/D_{eq})h_m \lambda (p_o - p_a) \quad \text{.......... (10)}$$

For a particular wind speed and diameter D_o, the coefficients h_c, h_m and h_r are fixed [12], and hence, for a particular value of D_{eq}, so are the terms $(D_o/D_{eq})(h_r + h_c)$ and $(D_o/D_{eq})h_m$. Representing these terms by K_b and H_b respectively reduces equation 10 to

$$J = K_b (t_o - t_a) + H_b \lambda (p_o - p_a) \quad \text{.......................... (11)}$$

Equations 6 and 11 can be combined to yield the following two equations for J

$$J = \frac{K_a H_b}{H_a + H_b}(t_s - t_o) + \frac{K_b H_a}{H_a + H_b}(t_o - t_a) + \frac{H_a H_b}{H_a + H_b}\lambda (p_s - p_a) \quad \text{.. (12)}$$

and

$$J = \frac{K_a K_b}{K_a + K_b}(t_s - t_a) + \frac{H_a H_b}{K_a + K_b}\lambda (p_s - p_a) + \frac{K_a(1 - H_a K_b)}{H_a K_b(K_a + K_b)}\dot{m}_o \quad \text{.... (13)}$$

where $\dot{m}_o$ is the rate of mass transfer (kg/s) from the outer surface of the homogeneous layer.

<u>Special Case</u>: In the special case where the rate of vapour transfer to the outer surface of the homogeneous layer equals the rate of vapour transfer from it, then both equations 12 and 13 reduce to

$$J = \frac{K_a K_b}{K_a + K_b}(t_s - t_a) + \frac{H_a H_b}{H_a + H_b}\lambda (p_s - p_a) \quad \text{.................... (14)}$$

<u>Dry Cylinder</u>: In the case of a completely dry cylinder surface, $p_s = p_a$ and equations 12, 13 and 14 each reduce to

$$J = \frac{K_a K_b}{K_a + K_b}(t_s - t_a) \quad \text{.. (15)}$$

<u>Practical Considerations</u>: Equations 12, 13, 14 and 15 provide a useful basis for investigating heat transfer from clothed humans. By analogy with the derivation of these equations, the heat transfer from a particular man, in a given clothing system and at a fixed wind speed, may be represented by equations of the form

$$J = \alpha(t_s - t_o) + \beta(t_o - t_a) + \gamma(p_s - p_a) \qquad (16)$$

$$J = \theta(t_s - t_a) + \varphi \dot{m}_o + \psi(p_s - p_a) \qquad (17)$$

$$J^* = \theta^*(t_s - t_a) + \gamma^*(p_s - p_a) \qquad (18)$$

$$J = \theta(t_s - t_a) \qquad (19)$$

where α, β, γ, θ, φ and ψ are constants. The asterisks on J^*, θ^* and γ^* in equation 18 denote that these quantities refer to the special case where vapour transfer to and from the outer clothing surface is equal, and in particular, no additional evaporation of sweat occurs from the clothing surface.

EXPERIMENTAL METHODS

Equipment: The experimental method is based on measuring the power supplied to a life sized copper manikin when in a state of thermal equilibrium. The manikin is designed to represent an averaged size man and it has a surface area of 1,85 m². Human sweating was simulated by manually wetting a high wicking nylon-cotton skin which fitted the manikin closely. The rate of evaporative mass transfer from the external clothing surface was measured as a rate of mass loss from the clothed manikin, which was located on an automatically operated beam balance with resolution of one gram. Mass was recorded every 15 sec. The average temperature of the copper surface of the manikin is controlled by a power recorder controller. The temperature of this surface (next to the cotton skin) is measured by means of 21 thermocouples which are distributed such that they each represent approximately the same area. An arithmetic average of these temperatures was taken as the mean temperature of the manikin surface, (mean skin temperature).

The manikin was situated within a chamber in which air motion is constant. Air is drawn from the chamber at floor level and reintroduced through a perforated ceiling. The average wind speed in the vicinity of the man, taken as the average of 60 anemometer readings was found to be 0,22 m/s. The temperature and relative humidity of the environment in the chamber was controlled during each experiment to within ± 0,5°C and 1% r.h. respectively. All temperatures were recorded on a 24 point recorder.

<u>Clothing</u>: The clothing tested in the present experiments was the U.S. Army's standard combat fatiques complete with boots and helmet. Apart from the helmet, this clothing is quite similar to the type of clothing commonly worn by workmen in industry.

<u>Procedure with dry skin</u>: The manikin was dressed and the power required to maintain a constant temperature at the manikin surface was then measured. Thermal equilibrium was assumed when the power being supplied to the manikin reached a constant level. The air temperature and the average surface temperature of the manikin were then measured. The manikin was then undressed and the procedure repeated a number of times in order to obtain random variability in the drape of the clothing.

<u>Procedure with wet skin</u>: The cotton skin of the manikin was wetted fully and the manikin was then dressed as quickly as possible. As above, the temperature at the manikin's surface was maintained at a constant level. When thermal equilibrium was reached power was measured. This procedure was repeated until repeatable measurements of power were achieved. The clothing was then considered to have reached a stable state of wetness. In this stable state experimental data were collected. Measurements were made over periods of approximately 10 minutes. The measuring period commenced as soon as the power to the manikin reached a constant level. The rate of decrease of mass yielded the average rate of moisture transfer, $\dot{m}_o$, into the surrounding environment. For each value of mean skin temperature (manikin surface temperature) this procedure was performed three times. Experimental measurements were made at five manikin surface temperatures in the range 27,9°C to 32,9°C.

<u>RESULTS</u>

Least squares multiple regressions were used to determine numerical values for the constants θ, φ, Ψ, θ^* and γ^* in equations 17, 18 and 19. The values are presented in Table 1. For the case of heat transfer from the manikin with a <u>dry skin</u>, equations 17, 18 and 19 are identical in their representation of the heat transfer process, and consequently $\theta = \theta^*$. The third group of constants in Table 1 have been derived by constraining the values of θ and θ^* to the value derived for the case of heat transfer from

the manikin with a dry skin. The predictive capability of equation 17 and 18, using the last two groups of regression constants presented in Table 1, is demonstrated in Figure 2.

DISCUSSION

Figure 2 shows that either equation 17 or equation 18 can be used to obtain an acceptable estimate of the heat transfer observed in the present study. The high correlation coefficients and low standard deviations presented in Table 1 support this statement. Furthermore, for practical purposes, Figure 1 indicates that the equations are equivalent: in terms of their respective theoretical derivations this equivalence implies that in the present study, the rate of vapour diffusion to the clothing surface equalled that which occurred from it. This implication is further supported by the close agreement between the constants θ and θ^*; their unconstrained least squares values differ by less than 5%.

Whether the equivalence between equations 17 and 18 extends much beyond the range of the present experiments is open to question. In hot humid environments with moderately high wind speeds a situation can arise, where in addition to the sweat which evaporates at the skin surface, a certain amount of sweat may be transferred mechanically (wicked) on to the clothing surface where it evaporates. When this occurs, equation 18 is not strictly valid. Equation 18 may also be inadequate for the purpose of predicting the heat transfer in those situations where condensation of evaporated sweat occurs within the clothing system. To establish the limitations of equation 18 will require systematic experimental investigation.

The present experiments have also shown that the sensible heat transfer properties of the clothing under test are substantially dependent on skin wetness. On the basis of equation 18, Table 1 shows the sensible heat transfer (in terms of the coefficient θ^*) to increase by as much as 32% when comparing the case of a dry skin to that of a wet skin. It is probable that the water absorbed up by the clothing from the wet skin caused the drape characteristics of the clothing to alter such that the amount of air trapped within the clothing was reduced. As the insulative

properties of the clothing used are due largely to trapped air [13], the analogy between diffusive heat and mass transfer [1, 9] suggests that the evaporative, or mass transfer properties of the clothing should be affected similarly.

Figure 2 (curve 1) shows that a systematic error will arise if the sensible heat transfer properties of the clothing system are assumed to be independent of skin, or clothing wetness. In the case where the parameter θ^* has been assumed to be independent of skin and clothing wetness, the regression analysis has caused evaporative heat transfer to be overestimated by 13%. Figure 2 (curves 1 and 3) shows that in spite of this compensating effect, when θ or θ^* are constrained to their dry skin value, the predicted heat transfer deviates systematically from that which was observed. The effect of skin and clothing wetness on the heat transfer properties of clothing systems has not previously been investigated systematically: the arguments presented here indicate the need for such experimentation.

A comparison of the equations developed in this study with those developed by Woodcock [15] and Nishi and Gagge [6, 7] indicates that their equations are equivalent to equation 18. These workers have assumed implicitly that the only site at which water evaporates, (or condenses) is the human skin surface.

Although the derivation of Nishi and Gagge's equation differs from that followed in this paper, their equation and equation 14 differ negligibly in detail. In recent publications Nishi, Gonzales and Gagge [7] and Nishi et al [8] have outlined procedures which can be followed to determine numerical values for their equivalents of the idealized heat transfer coefficients, K_a, K_b, H_a and H_b. Their method is based on the assumption that sensible heat transfer from the skin surface equals that which occurs from the clothing surface. Restated, this assumption is equivalent to that upon which equation 18 is based.

Woodcock [14] and subsequently Goldman [4] and Givoni and Goldman [5] have used two parameters to characterise the heat and mass transfer properties of clothing systems. The sensible heat transfer properties of the clothing are characterised by the well known clo value [2], I, while the mass transfer

properties are characterised by Woodcock's impermeability index, i_m. In relation to the present work (equation 18) these parameters are equivalent to the following terms.

$$I = \frac{(K_a + K_b)}{K_a K_b} = \frac{1}{\theta^*}$$

and $$i_m = \frac{H_a H_b}{K_a K_b} \frac{(K_a + K_b)}{(H_a + H_b)} \frac{\lambda}{s} = \frac{\gamma^*}{\theta^*} \frac{\lambda}{s}$$

where s is an essentially constant parameter which relates h_e to h_c [1,9] for sea level conditions. Considering the definition of K_a, K_b, H_a, H_b and s, it is clear that I and i_m are parameters which depend on many variable factors. Some of these factors have been considered by Givoni and Goldman [5] in their model to predict the rectal temperature response of humans to work, environment and clothing. In particular, the present experimentation has demonstrated the dependence of the clo value I on skin and clothing wetness. It is interesting to note that in terms of the above expression for i_m, this parameter may be independent of the wetness effect. (As γ^* and θ^* are expected to vary similarly, and in the same direction, their ratio may remain essentially constant.)

The present work supports the equations currently being used to calculate heat transfer from clothed humans; however, it has also emphasized the limitations of these equations, and in the form of equation 16, (or 15), it has provided a more general equation which may provide a means for overcoming this limitation. Adoption of this more general equation will depend, in practice, on the development of a convenient procedure for the application of the equation.

CONCLUSION

The theoretical analysis has shown that the equations developed by Woodcock, and Nishi and Gagge are a special case of a more general equation. The equations of these workers are not valid theoretically when sweat evaporates simultaneously at the skin and clothing surfaces. In relating these equations to experimental data, skin (and clothing) wetness has been identified as an important factor in the calculation of

sensible heat transfer from clothed humans: if this effect is ignored then the predicted heat transfer deviates systematically from that which occurs.

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TABLE 1

LEAST SQUARES REGRESSION CONSTANTS

FOR EQUATIONS 17 AND 18

CONDITION	EQUATION 17					EQUATION 18			
	θ	φ	γ	r	SD	θ^*	γ^*	r	SD
1 Dry Skin	4,71			0,9999	0,4	4,71		0,9999	0,4
2 Wet Skin	7,22	8,01	16,08	0,9996	2,4	6,89	23,81	0,9995	2,7
3 θ and θ^* Constrained	4,71	3,73	23,61	0,9993	3,4	4,71	26,99	0,9993	3,5

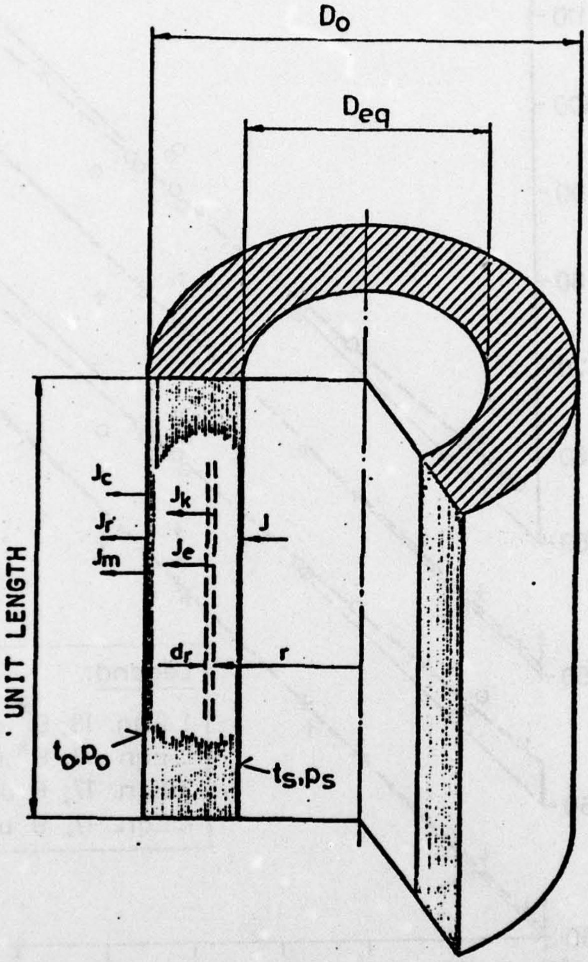

FIGURE 1 A UNIT LENGTH OF CYLINDER WRAPPED WITH A HOMOGENEOUS LAYER HAVING UNIFORM HEAT AND VAPOUR TRANSFER PROPERTIES

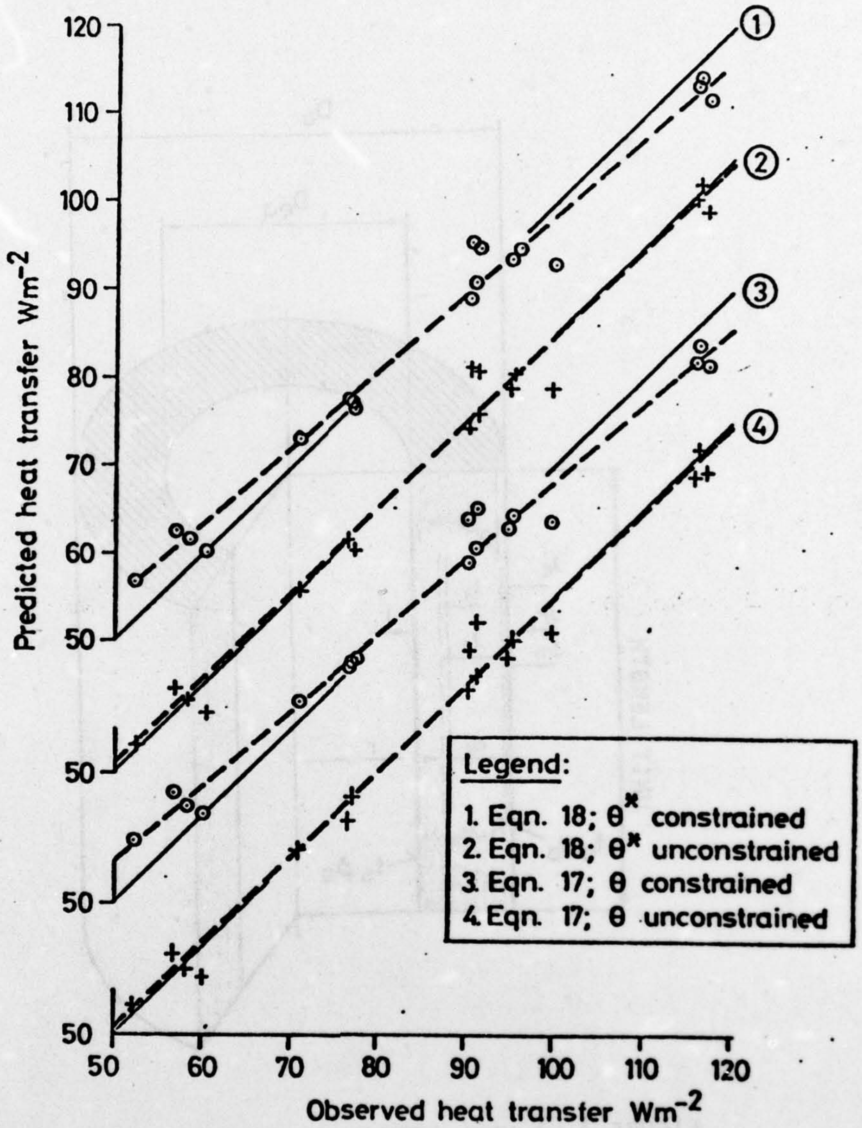

FIGURE 2 PREDICTED HEAT TRANSFER VERSUS OBSERVED HEAT TRANSFER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two equations have been derived for heat transfer from a cylinder. The cylinder had a wet surface and was wrapped with a layer having uniform properties. One equation is a special case of the other, a more general equation. The equation for the special case is equivalent to equations currently being used to describe heat transfer from clothed men. The special case implies that current equations are valid when sweat evaporates at the body skin surface only, i.e. no evaporation may occur at the clothing surface. Both (forms of the) equations

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gave good representation of the steady state data which were obtained from studies on a clothed, heated manikin with either a wet or dry skin ($r > 0.99$). The clothing resembled industrial clothing. Skin (and hence clothing) wetness increased the conductance of sensible heat by 32%. Failure to account for this effect caused insensible heat transfer to be underestimated by 13% and a systematic error was introduced into the prediction of total heat transfer.